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# Visible CWDM system design for Multi-Gbit/s transmission over SI-POF

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**ABSTRACT**

In order to increase the data rates of Multi-Gbit/s links based on large core step index (SI) plastic optical fibers (POF), different modulation scenes have been proposed. Another option is to use multiple optical carriers for parallel transmission of communication channels over the same fiber. Some designs to reach data rates of 14.77 Gb/s in 50 m, with 4 channels have been developed by off line processing. In this work, designs to test the potential of real Multi-Gbit/s transmission systems using commercial products are reported. Special care in designing low insertion loss multiplexers and demultiplexers is carried out to allow for greener solutions in terms of power consumption.

**Keywords:** In-building networks, visible CWDM, plastic optical fibers, multiplexer, demultiplexer, ADAS, automobile.

## 1. INTRODUCTION

Primarily due to the 'do-it-yourself' installation, easy maintenance and high bending tolerance, large core step index (SI) plastic optical fibers (POF) are considered more suitable than 50 mm core diameter multimode glass fibers or perflourinated plastic optical fibers in some applications such as home networking [1]. It is shown to be impossible to achieve more than 2 Gb/s for 50 m single-core SI-POF using eye-safe VCSEL transmitters. In order to increase the data rates of Multi-Gbit/s links based on SI-POF, different modulation scenes have been proposed by different authors such as CAP-64, QAM512 [2, 3], DMT and M-PAM. Another option is to use multiple optical carriers in a single POF for parallel transmission of communication channels over the same fiber [4]. As the channels are broadband and far away in comparison to long haul optical communication, they are referred to as course wavelength division multiplexing (CWDM) systems. Current proposals of visible CWDM over SI-POF are based on spectral grids [5] with channels between 400nm and 700nm using laser diodes (LDs) or light emitting diodes (LEDs). Some designs to reach data rates of 14.77 Gb/s, with 4 channels via up to 50 m of a SI−POF have been developed [6] using this approach but those rates are reached by offline-processing discrete multitone modulation.

Initially, transmission with SI–POF has been realized with only one channel, typically at 650 nm, reaching data rates of 100 Mb/s over links of 275 m [7]; even multi−gigabit transmission over links of 50 m has been reached [8]. Commercial systems based on SI-POF links able to provide data rates around 1 Gb/s over 50 m are already in the market but operating at a single wavelength [9]. SI-POF technology has also an application niche in providing a solution to the exponential growth of infotainment devices within the car, along with the proliferation of ADAS (Advanced Driver Assistance Systems), that has created a demand for a more efficient way to interconnect devices within the automobile. ADAS global market is substantially growing in recent years and requires increasing the available bandwidth, nowadays up to 1 Gb/s [10] and potentially in the near future to be increased up to 5Gb/s [11].

Apart from the physical transmission characteristics of SI-POF, it is equally important to consider the optical components introduced to deploy advanced WDM-based architectures. A typical WDM optical communication link requires, at the very least, both a multiplexer and a demultiplexer which provide additional insertion loss into the system.

This results in a decrease of the available optical power budget of the system leading to a bit-rate penalty. Most of the POF-based mux/demux prototypes reported in literature have been developed on the basis of interference filters and diffraction gratings. However, it has been previously stated that the use of gratings for WDM-POF applications probably leads to the best results in terms of insertion loss [12] in which typical insertion losses of ~5dB are usually expected. Improved designs are reported in [13, 14].

In this work, designs to test the potential of real Multi-Gbit/s transmission systems using commercial products are reported. Special care in designing low insertion loss multiplexers and demultiplexers is carried out. A comparison with reported data of off-line processing CWDM systems in terms of power consumption is included.

## 2. VISIBLE CWDM SI-POF SYSTEM

A real−time bidirectional link between two points (e.g. two personal computers, PC1 and PC2) at data rates of multiple Gb/s using *N* CWDM SI-POF channels is designed from a commercial 1 channel link at 1 Gb/s at 50m and novel MUX/DEMUX designs with low insertion losses and high crosstalk. The link schematic is shown in Figure 1.

The PCs are equipped with Gigabit Ethernet interfaces in combination with Media Converters (MCs) to generate and to read the data bits, respectively. The MCs transform the standard Gigabit Ethernet frames into *M*−PAM signals (called *Tx*−signals), and vice versa. In the transmitters (Txs), the different Tx−signals modulate the respective laser diode (LDs) or Light Emitting Diodes (LEDs). These optical signals are multiplexed in a SI−POF link up to 50m. A reflective diffraction grating based DeMux is used at the end of the link to split the different channels to their respective receivers (Rxs). At the receivers the optical signals are converted back to electrical signals (Tx−signals) by using a commercially available receiver [5], and finally, the Ethernet frames are recovered by the MCs.

(1)

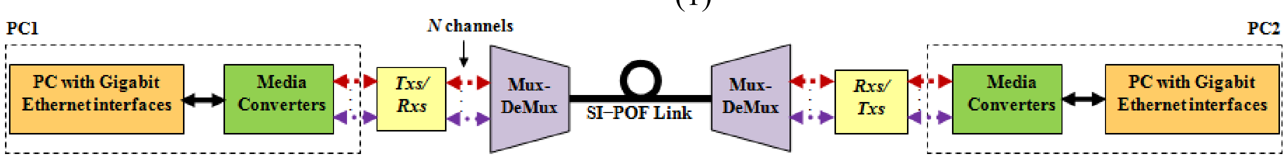


Fig. 1 Transmission scheme of the proposed SI-POF visible CWDM system with *N* channels between 400 and 700 nm.

### 2.1 Media Converters, transceivers and Power Budget Requirements

The Media Converters specifications and performance are reported in [9]. This commercial system can be used to set up a real time single channel link at 1 Gb/s link over 50 m of standard SI−POF using a light source at 650 nm with a transmission power of −3.15 dBm and total Insertion Losses (IL) up to 17.85 dB (at 25ºC) is.

Those MCs require a minimum power of -18dBm (at 650nm) at the receiver (including 2 dB losses of receiver coupling loss) to establish a 1Gb/s link using SI-POF.

### 2.2 Multiplexer and Demultiplexer

In this section, a new 5 channels low loss demultiplexer for SI−POF CWDM networks is presented. It is based on a collimator/focusing lens and a reflective diffraction grating. The diffraction grating has an area of 50 mm×50 mm, 600 grooves/mm and efficiency between 56% to 68% in the range from 400 to 650 nm. The grating area limits the collimation distance, or effective focal length (EFL), to be less than 45 m, in order to get a collimated beam diameter <

50 mm (this is an approximation considering SI−POFs with NA = 0.5). Therefore, the selected collimator/focusing lens has 50 mm diameter and 40 mm of EFL, in order to separate up to 5 channels, a distance greater than 1.3 mm. This guarantees channels with large a spectral bandwidth at -25 dB (up to 50nm). A detailed description of diffraction grating based demultiplexer design for SI−POF WDM networks is reported in [13].

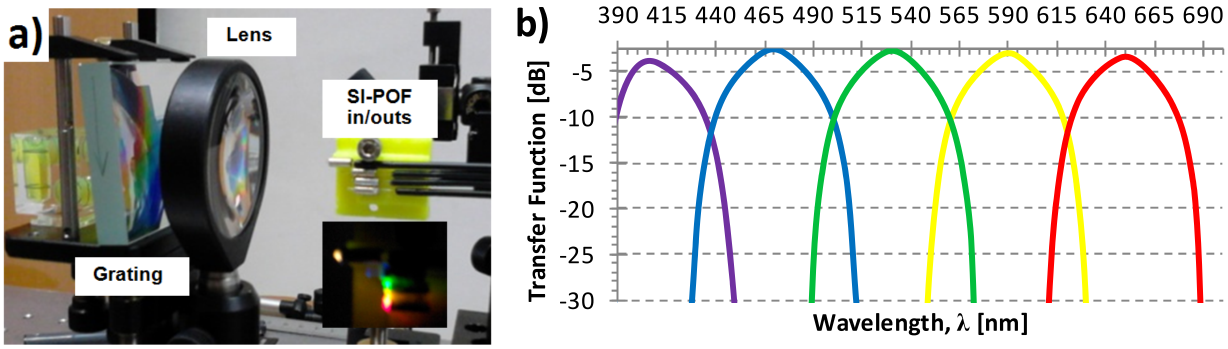


Figure 1. (a) Left: Mux-Demux experimental setup. (b) Right: Transfer function of a Mux-Demux configuration with 5 ports and 1 common fiber.

The DeMux experimental setup is shown in Fig. 2.a; it is made of only two optical elements and it has ~60 mm diameter and ~70 mm length. This Mux-Demux is based on a common port and *N* input/output ports, which represent the number of channels. Each input/output port has its own focusing distance due to the dispersion of the lens in the range from 400 to 650 nm, see an example in Fig. 2.a (1 common port and 3 input/output ports). The number of channels, crosstalk and insertion losses are highly dependent of the configuration used in the SI-POF input/output fibers. The transfer function shown on Fig. 2b is obtained using an optimized SI-POF input/outputs configuration based on 1 common fiber and 5 input/output ports separated a distance greater than 1.2 mm.

The IL measurements were done with the following procedure: 1) the light source is connected to the spectrometer using 3 m of SI−POF with mode filters next to the source and spectrometer, this measurement is the reference spectra (100% of transmission), 2) the 3 m of SI−POF is cut in half and each end is polished, 3) the SI−POF section attached to the light source is connected to the common port and the SI−POF section that is attached to the spectrometer is connected to the respective input/output port, 4) This procedure is repeated with the 5 input/output ports.

The transfer function of each input/output port in the range from 370 nm to 700 nm is shown in Fig. 2.b and the main parameters are reported on Table I.

*Table I. Basic parameters of the MUX/DEMUX*

| Central Wavelength [nm] | Spectral Bandwidth [nm] at -25dB | IL [dB] |
|---|---|---|
| 405 | 43 | 3.92 |
| 470 | 43 | 2.62 |
| 530 | 42 | 2.78 |
| 590 | 38 | 3.05 |
| 650 | 50 | 3.5 |

It is shown that the IL per channel of the proposed demultiplexer is less than 4 dB. This value includes the IL produced by two polished surfaces. IL uniformity in a 5 channel configuration is 1.3 dB, more than 1dB below the 4 channel configuration reported in [6] and it is reduced below 0.9 dB in a 4 channel configuration. It is also shown that the spectral bandwidth at -25 dB is higher than 38 nm. It is important to note that the measurements under −40dB are limited by the spectrometer sensitivity. This DeMux is compact and presents one of the best performances reported to date with only 2 optical elements. Current works of the authors are aimed to increase the number of channels to 8 keeping the IL below 5 dB.

## 3. PRELIMINARY RESULTS OF THE PROPOSED TRANSMISSION SYSTEM

The measured transfer function of the 5 input/output port, including 25 and 50 m of SI−POF and two Mux-Demux devices is shown in Fig 3.

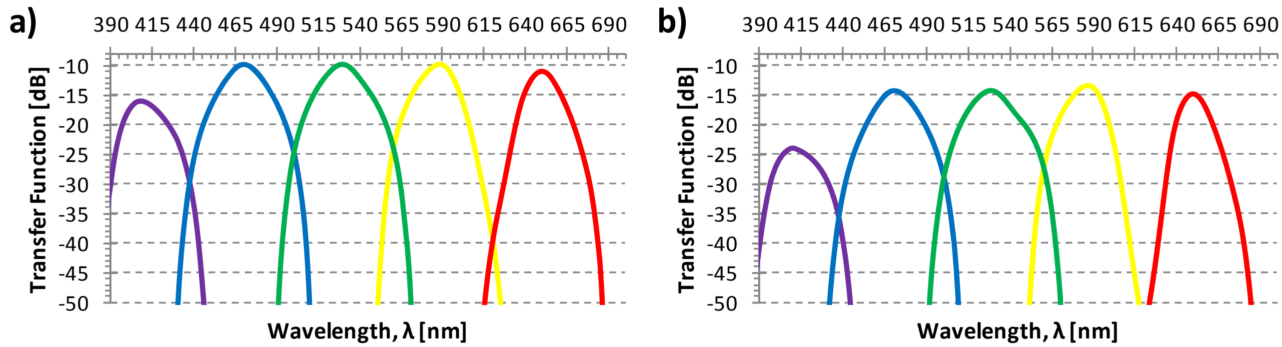


Figure 2. Transfer function of a bidirectional link using a visible CWDM system with 5 channels made of 2 Mux-DeMux devices: a) 25 m of SI-POF, b) 50m of SI-POF.

The overall system test has been done with only one channel at 650 nm, using the LD L650P0007 with an average transmitted power of 6 dBm (4 mW), and 50 m of SI−POF. In this case, the received power is of about −8.1 dBm (total IL of ~15 dB) which is enough to full fill the link budget and sensitivity requirements of the receiver [9].

On the other hand, the system produces an opened eye diagram with NRZ signals up to 333 MHz. Therefore, the bandwidth requirements for establishing the 1 Gb/s link are also full filled [9]. The system transmission bandwidth has been experimentally tested using the channel at 650 nm and a TCP bandwidth measurement tool (iperf). The results are shown in Fig.4.


Figure 4. Transmission Test with one channel at 650 nm and 50m of SI-POF. The test is done with a TCP bandwidth measurement tool (iperf) with 4 parallel streams. The resulting mean bandwidth is 814 Mbits/s.

The different channels at 405, 470, 530, 590 nm and 650 nm can be used to increase the transmission link capacity, up to 5 Gb/s.

## 4. POWER CONSUMPTION DISCUSSION

In the current system, a receiver sensitivity of -18dBm is required for a 1 Gb/s link proper operation (including 2dB loss at Rx). In a 25m length (see Fig. 3.a) fiber losses at 650nm are equal to -11dB, so the link is viable keeping the transmitter optical power at -3.5dBm, having a margin of 3.5dB. But in 50m length, fiber losses increase up to -15dB and transmitter optical power has to be increase up to 0dBm for keeping a margin of 3dB.

A CWDM configuration with 4 channels is going to be considered for comparison purposes with the solution reported in [6]. For the worst case channel, a power budget improvement of 3.6 dB is achieved (2.1 dB in the DEMUX IL and 1.5dB in the MUX IL), see Table I, in an overall power budget of 18dB. This loss saving can be used for reducing the transmitter output power in more than 3dB or a 50% power consumption reduction. In our experiment it is used a LD output power of 6 dBm, although only 0dBm were needed, meanwhile in [6] a 10 dBm optical source output power at around 650nm is used. Input optical powers up to 19 dBm are considered in [6] at other wavelenghts with higher MUX/DEMUX insertion losses.

## 5. CONCLUSIONS

A real–time bidirectional link at data rates of multiple Gb/s using *N* CWDM SI-POF channels has been designed from a commercial 1 channel link at 1 Gb/s at 50m and novel MUX/DEMUX designs with low insertion losses and high crosstalk. An improvement of more than 3 dB in power budget is achieved, in comparison with previous 4 channels CWDM SI-POF experiments. This loss saving can be used for reducing the transmitter output power implying a 50% power consumption reduction. The proposed designs can be scale up to an 8 channels system. Better Insertion Loss uniformity is also achieved.

## 6. ACKNOWLEDGEMENT

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